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Piping Failure Frequency Analysis for the Main Feedwater System in Domestic Nuclear Power Plants

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Abstract

The purpose of this paper is to analyze the piping failure frequency for the main feedwater system in domestic nuclear power plants(NPPs) for the application to an in-service inspection(ISI), leak before break(LBB) concept, aging management program(AMP), and probabilistic safety analysis(PSA). First, a database was developed for piping failure events in domestic NPPs, and 23 domestic piping failure events were collected. Among the 23 events, 12 locations of wall thinning due to flow accelerated corrosion(FAC) were identified in the main feedwater system in 4 domestic WH 3-loop NPPs. Two types of the piping failure frequency such as the damage frequency and rupture frequency were considered in this study. The damage frequency was calculated from both the plant population data and damage(s) including crack, wall thinning, leak, and/or rupture, while the rupture frequency was estimated by using both the well-known Jeffreys method and a new method considering the degradation due to FAC. The results showed that the damage frequencies based on the number of the base metal piping susceptible to FAC ranged from 1.26×10^{-3}/cr.yr to 3.91×10^{-3}/cr.yr for the main feedwater system of domestic WH 3-loop NPPs. The rupture frequencies obtained from the Jeffreys method for the main feedwater system were 1.01×10^{-2}/cr.yr and 4.54×10^{-3}/cr.yr for the domestic WH 3-loop NPPs and all the other domestic PWR NPPs respectively, while those from the new method considering the degradation were higher than those from the Jeffreys method by about an order of one.

Key Words : piping failure frequency, main feedwater system, flow accelerated corrosion

1. Introduction

The portion of nuclear piping is about 40% of the total nuclear components, and the total length of piping is about 100 km in a typical 1000MWe PWR. Except for some primary piping made of stainless steel, most of the nuclear piping is made of carbon steel. The operating experience shows that the carbon steel piping is very susceptible to flow accelerated corrosion(FAC) during plant operation.[1~3] 1,003 piping failure cases due to FAC among a total of 4,064 piping failure cases in the United States from 1961 to 1997 were reported.[4] In general, piping failure due to FAC increases as the nuclear power plants(NPPs) aged. So piping failure due to FAC has been regarded as an important safety concern in the nuclear field.[5,6]

As a measure for nuclear piping reliability, the piping failure frequency is widely used. The piping failure frequency is generally used in the failure trend analysis for an application to in-service inspection(ISI), leak before break(LBB) concept, and the aging management program(AMP). It is also mainly used in the re-evaluation of the initiating event frequency for the probabilistic safety analysis(PSA). The various evaluation methods of the piping failure frequency have been developed in order to estimate quantitatively the effect of piping failure on the PSA.[7,8]

In this study, a database was developed for piping failure events in domestic NPPs, and 23 piping failure events in domestic NPPs were collected. Among the piping failure events in domestic NPPs, the piping failures due to FAC in the main feedwater system were investigated in detail including the root cause analysis.

Two types of the piping failure frequency such as the damage frequency and rupture frequency were considered in this paper.

For the damage frequency evaluation, we defined damage as flaws exceeding the criterion required in the ASME Code Sec. XI including crack, wall thinning, leak, and/or rupture.[9] The rupture is generally defined as a severe piping failure with a leak exceeding 50gpm. The damage frequency can be used for the failure trend analysis, while the rupture frequency can be used for the PSA application in general.

The rupture frequency is based on the number of events where a system is unavailable due to a leak and/or break. The rupture frequency was evaluated using the well-known Jeffreys method in this paper.[8] The Jeffreys method is based on real events having a leak and/or rupture. If the system has degradation without a leak and/or rupture, the rupture frequency of the system is expected to be potentially higher than that of the system having no experience of degradation. However, the Jeffreys method gives the same rupture frequency for the both cases.

In this study, a new method considering the degradation to predict the rupture frequency for the piping system having degradation due to FAC without a leak and/or rupture was proposed for the main feedwater system.

2. Development of Piping Failure Database

In order to perform the piping failure frequency analysis, a piping failure database for the domestic NPPs was developed with 115 data fields for the event data, plant population data, and service history data. Piping failure events in the domestic NPPs from the initial commercial operation date to the end of 2001 were collected. As listed in Table 1, a total of 23 piping failures were identified in the main feedwater system(MF), chemical volume control system(CVCS), primary sampling system(PS), essential service water system(ESW), CANDU failed fuel location system(FF), and the

Table 1. Piping Failure Events in Domestic NPPs by the End of 2001

No	Rx Type	System	Nominal Diameter (in)	Root Cause	Leak
P1	WH-3	MF	18	FAC	no leak (WT)
P2	WH-3	MF	18		
P3	WH-3	MF	18		
P4	WH-3	MF	18		
P5	WH-3	MF	18		
P6	WH-3	MF	18		
P7	WH-3	MF	18		
P8	WH-3	MF	18		
P9	WH-3	MF	18		
P10	WH-3	MF	18		
P11	WH-3	MF	18		
P12	WH-3	MF	18		
P13	WH-3	CVCS	2	Vibration	leak
P14	WH-3	CVCS	3/4		
P15	WH-3	CVCS	3/4		
P16	WH-3	CVCS	2		
P17	KSNP	PS	3/8	TF	leak
P18	FR	ESW	28	Corrosion	leak
P19	FR	ESW	10		
P20	FR	ESW	28		
P21	FR	ESW	35		
P22	CANDU	FF	1/4	TF	leak
P23	CANDU	PF	4	TF	leak

CANDU purification system(PF). The root causes of the events were analyzed as FAC, vibration, thermal fatigue(TF), or corrosion. Among the 23 cases, 12 cases were wall thinning(WT) due to FAC in the main feedwater system of domestic WH 3-loop NPPs. There was no leakage in the degraded main feedwater piping.

3. Piping Failure in Domestic Main Feedwater System

3.1. Event Description

In 1999, severe degradation of wall thinning in

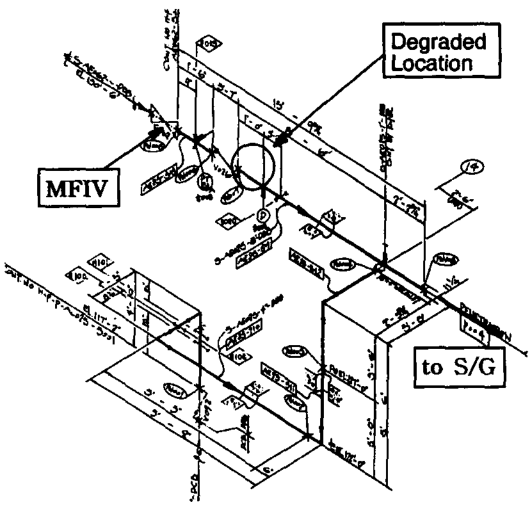

Fig. 1. Location of Pipe Wall Thinning in Main Feedwater System

the main feedwater system of one domestic WH 3-loop NPP was reported. The same type of piping degradation was found in the main feedwater system of 3 other domestic WH 3-loop NPPs by an augmented inspection using ultrasonic testing(UT). a total of 12 degraded locations were identified in the main feedwater system.[10,11]

The thinned area was located in the outlet of the check valve(V026) between the steam generator(S/G) and the main feedwater isolation valve(MFIV) as shown in Fig. 1 which is the isometric drawing from MFIV(FV052) for containment penetration(P004). The degraded piping has an outer diameter(Do) of 457.2mm(18inch), a nominal thickness (t_{nom}) of 23.83mm, and a minimum design wall thickness (t_{min}) of 17.50mm. The piping material of the degraded location was SA 333 Gr. 6. The root cause of the failure was analyzed as FAC.[10~12] Any other failure cases in the main feedwater system of domestic NPPs exceeding the criterion given in the ASME Code Sec. XI have not been reported.

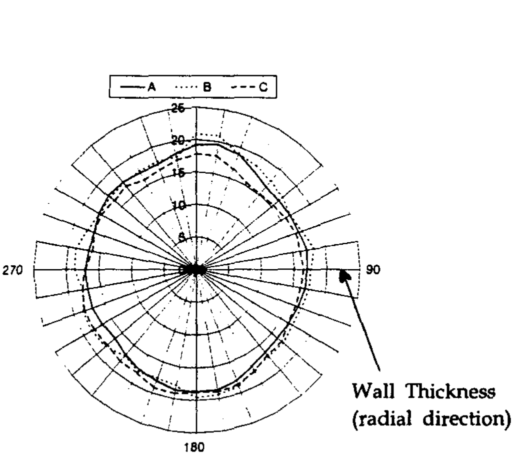

Fig. 2. Circumferential Wall Thickness of 3 Degraded Loops(A, B, C) in the Main Feedwater System in One Domestic NPP

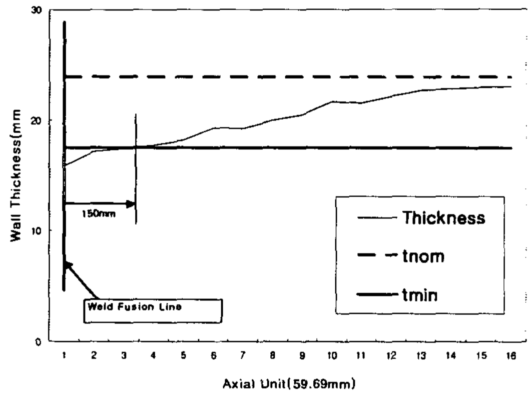

Fig. 3. Axial Wall Thickness from Weld Fusion Line in one Main Feedwater System in one Domestic NPP

3.2. Impact on Safety and Integrity

Although the main feedwater system has no safety function, the degraded area is designed as the ASME Code Class 2 because a pipe rupture between the S/G and the MFIV can cause a large loss of the secondary coolant from the S/G. So this event in the main feedwater system of the domestic WH 3-loop NPPs is regarded as a potential safety concern.

In order to evaluate the impact on the piping integrity, a detailed configuration of the degraded area by using UT was measured.

Fig. 2 shows the circumferential wall thickness of the 3 loops(A, B, and C) in one degraded main feedwater system. The figure shows that the wall thinning occurred along the entire circumferential direction and the requirement of the minimum wall thickness(t_{min}) given in the ASME Code Sec. XI[9] and Sec. III[13] was not satisfied at some portions.

The wall thinning for the axial direction is shown in Fig. 3. As shown in the figure, the pipe wall thinning was extended up to about 750mm from the weld fusion line in the axial direction and an axial length of about 150mm from the weld fusion line is unacceptable according to the requirement of the minimum wall thickness(t_{min}).

Because the requirements given in the ASME Code Sec. III[13], Sec. XI[5], and the Code Case N-597[14] were not satisfied, the degraded piping was replaced with new SA 106 Gr. C piping for a continuous plant operation.

3.3. Estimation of Wear Rate

The minimum pipe wall thickness in the 12 degraded areas was measured as 14.99mm by using UT. So, the maximum wall thinning depth due to FAC is 8.84mm. Using both this wall thinning depth and the duration of the plant's commercial operation, the maximum wear rate is estimated as 0.733mm/yr after the plant's commercial operation.

The wear rate based on the critical reactor year(cr.yr) can be obtained as 0.916mm/cr.yr by using the average conversion factor of 0.8, which is generally used in calculating the critical year from the commercial operation year.

4. Evaluation of Piping Failure Frequency for Main Feedwater System

Two types of the piping failure frequency such as the damage frequency(F_D) and rupture frequency(F_R) were considered in this study.

4.1. Damage Frequency of Main Feedwater System

Damage frequency is generally used in the failure trend analysis for application to an in-service inspection(ISI), leak before break(LBB) concept, and aging management program(AMP). In this study, damage is defined as a failure having flaws, which do not satisfy the regulatory requirement of the ASME Code Sec. XI, including crack, wall thinning, leak, and/or rupture.[5]

The damage frequency(F_D) for a specific diameter in a specific system can be defined as [15]

$$F_D = \frac{N_{j,event}}{\sum_{i=1,n} N_{i,j} \times Y_i} \quad (1)$$

, where $N_{j,event}$ is the number of damage events for a specific pipe diameter 'j' in the system. The denominator represents the pipe population data. 'n' is the number of NPPs having the same reactor type 'i', Y_i is each plant's operation year, and $N_{i,j}$ is the pipe population data such as weld count, the number of spools, or the number of the base metal piping for a specific pipe diameter 'j' in a specific system.

For the degraded event in the main feedwater system of the domestic WH 3-loop NPPs as described in Ch. 3 of this paper, the damage frequency can be obtained as follows;

The number of damage events($N_{j,event}$) and the number of domestic WH 3-loop NPPs are 12 and 4 respectively. The sum of the operation years(Y_i) by the end of 2001 is 61.83yr or 49.47cr.yr. As a measure of the pipe population data($N_{i,j}$), the number of the base metal piping susceptible to FAC was considered in this study. As the component boundary for $N_{i,j}$ in the main feedwater system, three cases are considered in this paper such as the piping in the entire main feedwater system from the main feedwater pump to the steam generator(Case 1), piping in the portion of the main feedwater system which has the same design condition(design temperature of 600°F and design pressure of 1,185psi) at the degraded location(Case 2), and piping in the safety class portion of the main feedwater system(Case 3).

Table 2. Damage Frequency(F_D) of 18inch Main Feedwater System in Domestic WH 3-Loop NPPs

	Case	No. of Base Metal Piping with 18" OD (per plant)	Damage Frequency (1/cr.yr)
1	Entire MF	192	1.26×10^{-3}
2	Same Design Condition	62	3.91×10^{-3}
3	Safety Class	65	3.73×10^{-3}

For the three cases, the numbers of the piping having an outer diameter of 18inch in the main feedwater system of domestic WH 3-loop NPPs are 192, 62, and 65, respectively. Table 2 represents the damage frequency for the 3 cases above. As listed in the table, the damage frequencies for the three cases are easily calculated as 1.26×10^{-3}/cr.yr, 3.91×10^{-3}/cr.yr and 3.73×10^{-3}/cr.yr, respectively.

4.2. Rupture Frequency of Main Feedwater System

The rupture frequency is mainly used in both the re-evaluation of the initiating event frequency and the system unavailability evaluation for the probabilistic safety analysis. The rupture frequency is based on the number of events where a system is unavailable due to a leak and/or break. The rupture frequency is generally calculated by using the Jeffreys method.[8] The Jeffreys method is based on 'real' events occurring such as a leak and/or rupture.

There, however, are various types of failure in the piping system such as a leak and/or rupture in the system(Type 1), no rupture and/or leakage, but some degradation in the system(hereafter, degradation is defined as the failure without a rupture and/or leak)(Type 2), and no failure including degradation in the system(Type 3). The Jeffreys method gives the same rupture frequency for Type 2 and Type 3. However, the rupture frequency of Type 2 is expected to be potentially higher than that of Type 3.

In this study, a method to predict the rupture frequency for the piping system having degradation without a leak and/or rupture(Type 2) was proposed for the main feedwater system having degradation of FAC.

4.2.1. Jeffreys Method

The rupture frequency by the Jeffreys method ($F_{R\text{-}Jeffreys}$) is as follows;[8]

$$F_{R-Jeffreys} = \frac{(n+0.5)}{T} \qquad (2)$$

, where n is the number of ruptures and/or leaks and T is the operation year.

By the end of 2001, T was 49.47cr.yr for 4 domestic WH 3-loop NPPs, and n was zero because there was no leak or rupture in the main feedwater system. So, the rupture frequency by the Jeffreys method can be estimated as 1.01×10^{-2}/cr.yr for the domestic WH 3-loop NPPs.

The rupture frequency of the domestic WH 3-loop plants was compared with the 12 domestic PWRs. The operation year of the 12 domestic PWRs was 110.11cr.yr by the end of 2001. The rupture frequency by the Jeffreys method can be estimated as 4.54×10^{-3}/cr.yr for the main feedwater system of the 12 domestic PWRs.

In the United States, 2 events of break/leak in the feedwater system were reported from 1987 to 1995. The operation year during the period was 729cr.yr. The rupture frequency of the feedwater system in the US can be estimated as 3.43×10^{-3} /cr.yr using the above Eq. (2).[8]

The rupture frequency(4.54×10^{-3}/cr.yr) of the main feedwater system for the domestic PWRs is slightly higher than that(3.43×10^{-3}/cr.yr) for the US.

4.2.2. Degradation Method

As mentioned in Ch. 3 in this paper, severe degradation due to FAC has been reported for the main feedwater system of domestic WH 3-loop NPPs. In this study, a new model to predict the rupture frequency based on the FAC degradation mechanism is proposed as follows; (Hereafter, the model is called the degradation method.)

The rupture frequency by the degradation method($F_{R\text{-}Degradation}$) is defined as

$$F_{R-Degrdation} = \frac{(n_D+0.5)}{T_p} \qquad (3)$$

, where n_D is the number of degradations and T_p is the prediction time to a rupture.

The degradation method has three steps as follows; the evaluation of the maximum allowable wall thickness at which an unstable failure occurs(Step 1), the calculation of the prediction time T_p to reach the maximum allowable wall thickness by the degradation due to FAC(Step 2), and the evaluation of the rupture frequency with T_p and n_D by using Eq. (3)(Step 3).

This degradation method for the rupture frequency may be applied to a failure in which the degradation rate such as the wear rate for the FAC and the crack growth rate for the fatigue cracking or stress corrosion cracking is well defined and can be measured.

Step 1

The maximum allowable thickness can be obtained from the comparison of the maximum allowable pressure with the design pressure.

The maximum allowable thickness is defined as the thickness at which the unstable failures such as the ovalization, the local buckling, the cracking and/or the leak occur in the thinned piping. The rupture may not be induced from the failures in the thinned piping. This means that the rupture frequency by the degradation method in this study basically means the frequency for the integrity failure. We, however, use the maximum allowable pressure at which the piping burst(or leak) occurs under the pressure loading condition given as the Battelle method[16] and FEM the method[17]. The experiences using the thinned piping showed that both methods give us the maximum allowable pressure at which the piping burst(or leak) occurs under a given pressure loading condition[17]. As described in the introduction, the rupture is defined as the state at which the pipe is unavailable due to a leak and/or break. This means that the maximum allowable wall thickness in this study is basically the pipe rupture wall thickness according to the definition of the rupture in this study.

The Battelle method is based on the model that the maximum pressure of a wall thinning piping is controlled by the plastic collapse by tensile strength, while the FEM method is based on the 3 dimensional FEM model for the wall thinning piping. The maximum allowable pressures from the Battelle method and the FEM method are given in Eqs. (4) & (5), respectively.

$$P_{\max-Battelle} = \frac{2t}{D_m}\sigma_u\left[1-\frac{a}{t}\left(1-\exp\left(-0.157\frac{L}{R(t-a)}\right)\right)\right] \quad (4)$$

$$P_{\max-FEM} = \frac{2t}{D_i}\sigma_o\left[A_2\left(\frac{L}{\sqrt{Rt}}\right)^2+A_1\left(\frac{L}{\sqrt{Rt}}\right)+A_o\right] \quad (5)$$

, where σ_u is the tensile strength, σ_y is the yield stress, and σ_o, A_2, A_1, and A_0 are as follows;

$$\sigma_o = \sigma_y + 68.95\ MPa \quad (6)$$

$$A_2 = -0.0148\left(\frac{a}{t}\right)^2+0.0339\left(\frac{a}{t}\right)-0.002 \quad (7)$$

$$A_1 = 0.1698\left(\frac{a}{t}\right)^2-0.4129\left(\frac{a}{t}\right)+0.019 \quad (8)$$

$$A_0 = 0.3156\left(\frac{a}{t}\right)^2+0.1619\left(\frac{a}{t}\right)+0.1637 \quad (9)$$

For the degraded location of the main feedwater system in the domestic WH 3-loop NPPs, the values of t, D_m, D_i, and R are 23.83, 442.4, 409.5, and 216.7mm, and the values of σ_u and σ_y are 70ksi and 40ksi, respectively. The L value was measured as 746mm with the maximum wall thinning depth of 8.84mm. The design pressure (P_d) at the degraded area is 1.185ksi.

Fig. 4 shows the relative maximum allowable pressure for the design pressure for the thinned area in the main feedwater system. As shown in the figure, the relative pressure has a margin of 1 to 6.5 for the whole pipe wall thickness. It means that the maximum allowable thickness for the thinned area in the main feedwater system is the total wall thickness of 23.8mm.

Step 2

In order to evaluate the prediction time(T_p) to reach the maximum allowable wall thickness by the degradation due to FAC, the wear rate due to FAC is necessary. As estimated in Ch. 3 in this paper, the maximum wear rate of the degraded main feedwater piping was 0.733mm/yr. Using this wear rate, the prediction time(T_p) to reach the maximum allowable thickness of 23.83mm by FAC can be determined as 32.51yr based on the operation year or 26.01cr.yr based on the critical year. It means that the main feedwater piping of

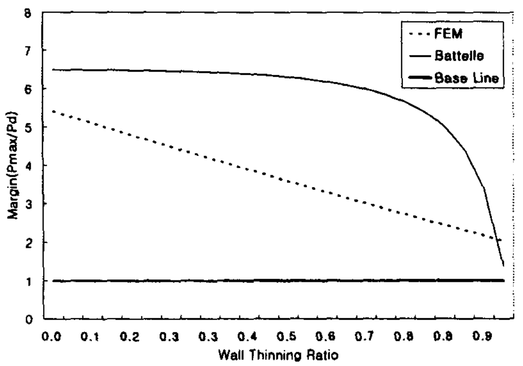

Fig. 4. Max Allowable Pressure for the Thinned Area in Main Feedwater System

domestic WH 3-loop NPPs would be ruptured after 26.01 cr.yr from the initial commercial operation if they were not found during the plant operation.

Step 3

With the values of n_D=12 and T_p=104.03cr.yr for the 4 domestic WH 3-loop NPPs, the rupture frequency is obtained from Eq. (3) as 1.20×10^{-1} /cr.yr for the main feedwater system in the domestic WH 3-loop NPPs. The total critical years for all the 12 domestic PWRs under operation as of Dec. 31, 2001 are estimated as 273.74cr.yr. Based on the assumption that further degradation, leak, and/or rupture would not occur, the rupture frequency for the main feedwater system in all the domestic PWRs is calculated as 4.57×10^{-2}/cr.yr.

Table 3 summarizes the results of the rupture frequencies from the Jeffreys method and the degradation method including the case in the United States. As listed in Table 3, the rupture frequencies for the main feedwater system in the domestic PWRs are similar to that in the United States based on the Jeffreys method. However, the rupture frequencies from the degradation method were higher than those from the Jeffreys method by about an order of one.

5. Conclusions

In this study, a database was developed for piping failure events in domestic NPPs, and 23 domestic piping failure events were collected. Among the 23 events, 12 degraded locations of wall thinning due to flow accelerated corrosion(FAC) in the main feedwater system in the 4 domestic WH 3-loop NPPs were identified.

Two types of the piping failure frequency such as the damage frequency and rupture frequency were estimated in this study. In particular, the rupture frequency was calculated using a new method based on piping degradation in addition to the well-known Jeffreys method.

The results showed that the damage frequencies based on the number of the base metal piping susceptible to FAC ranged from 1.26×10^{-3}/cr.yr to 3.91×10^{-3}/cr.yr for the main feedwater system of the domestic WH 3-loop NPPs.

The rupture frequencies obtained from the Jeffreys method for the main feedwater system were 1.01×10^{-2}/cr.yr and 4.54×10^{-3}/cr.yr for the domestic WH 3-loop NPPs and all the other domestic PWR NPPs respectively, while those

Table 3. Comparison of Rupture Frequency for Main Feedwater System

Method	Rx Type under Evaluation	n	Critical year (cr.yr)	Rupture Frequency (1/cr.yr)
Jeffreys Method	Domestic WH 3-Loop	0	49.47	1.01×10^{-2}
	Domestic PWRs	0	110.11	4.54×10^{-3}
	USA PWR/BWR [8]	2	702	3.43×10^{-3}
Degradation Method	Domestic WH 3-Loop	12	104.03	1.20×10^{-1}
	Domestic PWRs	12	273.74	4.57×10^{-2}

from the new method considering the degradation were higher than those from the Jeffreys method by about an order of one.

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